Bayesian Semiparametric GARCH Models

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Outline

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Motivation

- The GARCH model of Bollerslev (1986) has been useful in modelling volatilities of asset returns.
- Let $y = (y_1, \cdots, y_n)'$ denote a vector of $n$ observations of an asset return. A GARCH(1,1) model is often specified as

$$y_t = \sigma_t \varepsilon_t,$$

$$\sigma_t^2 = \omega + \alpha y_{t-1}^2 + \beta \sigma_{t-1}^2,$$  \hspace{1cm} (1)

where $\varepsilon_t$, for $t = 1, 2, \cdots, n$, are independent.
- The assumption of conditional normality of $\varepsilon_t$ has contributed to early successes of GARCH models.
- For example, the QMLEs of parameters are consistent when the first two moments of $y_t$ are correctly specified.

Problems

- However, enough evidence has shown that it is possible to reject the assumption of conditional normality.
- This has motivated the investigation of other specifications of the conditional distribution of errors in GARCH models, such as the Student $t$ and other heavy-tailed distributions.
- Any assumption on the analytical form of the error density is only an approximation to the unknown true error density.
- Moreover, it is very important to investigate the distribution of response, which is implied by the error density.
- Some investigations have been focused on parameter estimation for (G)ARCH models without assumptions on the analytical form of the error density.
A Semiparametric Approach

- Engle and González-Rivera (1991) proposed a semiparametric GARCH model without assumptions on the analytical form of error density.

- The error density was estimated nonparametrically based on residuals, which were obtained by applying either the QMLE (assuming conditional normality) or OLS.

- The parameters of the semiparametric GARCH model were estimated by maximising the log-likelihood constructed through the estimated error density.

- Their Monte Carlo study showed that this semiparametric approach could improve the efficiency of parameter estimates up to 50% against QMLEs obtained under conditional normality.

Limitations and Our Aims

- Their likelihood is affected by initial parameter estimates.

- Their semiparametric estimation uses the data twice because residuals have to be pre-fitted to construct likelihood.

- Their derived semiparametric estimates of parameters would not be used again to improve the error density estimator.

- We propose to approximate the true error density by a mixture of \( n \) normal densities, which have a common variance and individual means at the errors. This mixture density has the form of kernel density estimator of the errors.

- We treat the re-parameterised bandwidth as an additional parameter and investigate the likelihood and posterior under this mixture density of errors.
A location-mixture of $n$ Gaussian densities

- We assume that the unknown density of $\varepsilon_t$ denoted as $f(\varepsilon_t)$, is approximated by a location-mixture density:

$$f(\varepsilon_t; h) = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{h} \phi \left( \frac{\varepsilon_t - \varepsilon_i}{h} \right),$$

for $t = 1, 2, \ldots, n$, where $\phi(\cdot)$ is the Gaussian PDF, and the component Gaussian densities have a common variance $h^2$ and different means at $\varepsilon_i$, for $i = 1, 2, \ldots, n$.

- From the view of kernel smoothing, this mixture error density is a kernel density estimator of errors with $h$ the bandwidth. Therefore, we call $f(\varepsilon; h)$ the mixture (or kernel-form) error density, where $h$ is called either the standard deviation or bandwidth, which determines the performance of $f(\varepsilon_t; h)$.

Our contribution

- We propose to approximate the unknown error density by the kernel-form error density, based on which we are able to construct the likelihood.

- We choose prior densities for the two types of parameters and obtain the posterior of all parameters. Bayesian sampling is then used to sample these parameters.

- We use this semiparametric GARCH model to compute value-at-risk (VaR).
In our investigations, we focused on the conditional density of errors, and we considered the GARCH(1,1) model:

\[ y_t = \sigma_t \varepsilon_t, \]
\[ \sigma_t^2 = \omega + \alpha y_{t-1}^2 + \beta \sigma_{t-1}^2, \]  

where \( \omega > 0, \alpha \geq 0, \beta \geq 0 \) and \( \alpha + \beta < 1 \).

- Strictly speaking, conditional on information available at \( t - 1 \) denoted as \( I_{t-1} \), the density of \( \varepsilon_t \) denoted as \( f(\varepsilon_t) \), is unknown.
- When \( f(\varepsilon) \) is assumed to be known, the likelihood is

\[ \ell_0(y|\omega, \alpha, \beta) = \prod_{t=1}^{n} \frac{1}{\sigma_t} f \left( \frac{y_t}{\sigma_t} \right). \]

- \( f(\varepsilon) \) could be the Gaussian, Student \( t \), and a mixture of several Gaussian densities.
A location-mixture density of $n$ Gaussian densities

- We propose a location-mixture density as the error density:

$$f(\varepsilon; h) = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{h} \phi \left( \frac{\varepsilon - \varepsilon_i}{h} \right),$$

where the component Gaussian densities have a common variance $h^2$ and individual means at individual errors.

- In some investigations on asymptotic properties of parameter estimators, bandwidth depends on sample size $n$ and approaches zero as $n \to \infty$.

- We re-parameterise $h$ as $\tau n^{-1/5}$, where $n^{-1/5}$ is the optimal convergence rate under AMISE. Hereafter, bandwidth is denoted as $h_n = \tau n^{-1/5}$.

Benefit of the mixture error density

- $f(\varepsilon; h_n)$ has the form of kernel density estimator of errors.

- In terms of kernel density estimation based on directly observed data, Silverman (1978) proved that a kernel density estimator approaches the underlying true density as $n \to \infty$.

- Therefore, it is reasonable to expect that $f(\varepsilon; h_n)$ approaches $f(\varepsilon)$ as the sample size $n$ increases.

- $f(\varepsilon_t; h_n)$ differs from the kernel density estimator of residuals calculated through pre-estimated parameters. This mixture density is defined conditional on model parameters:

$$f(\varepsilon_t; h_n) = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{h_n} \phi \left( \frac{\varepsilon_t - y_i / \sigma_i}{h_n} \right),$$

where $\sigma_i^2 = \omega + \alpha y_{i-1}^2 + \beta \sigma_{i-1}^2$, for $i = 1, 2, \ldots, n$. 
Benefit of the mixture error density (2)

- To construct likelihood, we use the leave-one-out:
  \[
  f(\varepsilon_t|\varepsilon_(t); h_n) = \frac{1}{n-1} \sum_{i=1, i \neq t}^{n} \frac{1}{h_n} \phi \left( \frac{\varepsilon_t - \varepsilon_i}{h_n} \right). \tag{5}
  \]

- The density of \( y_t \) is estimated by
  \[
  f_Y(y_t|y_(t); \theta) = \frac{1}{(n-1)\sigma_t} \sum_{i=1, i \neq t}^{n} \frac{1}{h_n} \phi \left( \frac{y_t/\sigma_t - y_i/\sigma_i}{h_n} \right). \tag{6}
  \]

- In the density function of \( y_t \) given by (6), \( h_n \) and \( \sigma_t \) always appear in the form of the product of the two:
  \[
  h_n^2 \sigma_t^2 = h_n^2 \omega + h_n^2 \alpha y_{t-1}^2 + \beta h_n^2 \sigma_{t-1}^2. \tag{7}
  \]

Likelihood

- \( h_n^2 \) and \( \omega \), as well as \( h_n^2 \) and \( \alpha \), cannot be separately identified. If \( \omega \) (or \( \alpha \)) is assumed to be a known constant, all the other parameters can be separately identified.

- In adaptive estimation for ARCH models, \( \omega \) was restricted to be zero by Linton (1993) and one by Drost and Klaassen (1997).

- In light of the fact that the unconditional variance of \( y_t \) is \( \omega/(1 - \alpha - \beta) \), we assume that \( \omega = (1 - \alpha - \beta)s_y^2 \).

- When the return series is pre-standardised, the value of \( \omega \) would be assumed to be \( (1 - \alpha - \beta) \), which is the same as what Engle and Gonzalez-Rivera (1991) assumed for \( \omega \) in their GARCH model.
Likelihood and Choices of Priors

- The parameter vector is $\theta = (\sigma^2_0, \alpha, \beta, \tau^2)'$, and the restrictions are: $0 \leq \alpha < 1$, $0 < \beta < 1$ and $0 < \alpha + \beta < 1$.

- The likelihood of $y = (y_1, y_2, \ldots, n)'$, for given $\theta$, is

$$
\ell(y|\theta) = \prod_{t=1}^{n} \left\{ \frac{1}{(n-1)\sigma_t} \sum_{i=1, i \neq t}^{n} \frac{1}{h_n} \phi \left( \frac{y_t/\sigma_t - y_i/\sigma_i}{h_n} \right) \right\}. \tag{8}
$$

- Conditional on model parameters, this likelihood function is the one used by the likelihood cross-validation in choosing bandwidth for the kernel density estimator of standardised $y_i$.

- The prior of $\alpha$ is the uniform density on $(0,1)$, and the prior of $\beta$ is the uniform density on $(0,1 - \alpha)$.

Prior Choices and Posterior

- As $(\tau n^{-1/5})^2$ is the variance of component Gaussian densities in the mixture, we assume $(\tau n^{-1/5})^2$ follows an inverse Gamma distribution denoted as IG($a_\tau$, $b_\tau$). Therefore, the prior of $\tau^2$ is

$$
p(\tau^2) = \frac{b_\tau^{a_\tau}}{\Gamma(a_\tau)} \left( \frac{1}{\tau^2n^{-2/5}} \right)^{a_\tau+1} \exp \left\{ -\frac{b_\tau}{\tau^2n^{-2/5}} \right\} n^{-2/5}.
$$

- The prior of $\sigma^2_0$ is assumed to be either the log normal density with mean zero and variance one or the density of IG(1,0.05).

- The joint prior of $\theta$ denoted as $p(\theta)$, is the product of the marginal priors of $\alpha$, $\beta$, $\tau^2$ and $\sigma^2_0$.

- The posterior of $\theta$ for given $y$ is proportional to the product of the joint prior of $\theta$ and the likelihood of $y$ for given $\theta$:

$$
\pi(\theta|y) \propto p(\theta) \times \ell(y|\theta).
$$
• We used the random-walk Metropolis algorithm to sample parameters of the GARCH(1,1) model of daily returns of the S&P 500 index.

• The sample period is from 03/01/2007 to 30/06/2011, and the sample size is $n = 1131$.

• We estimated the parameters in the semiparametric GARCH(1,1) model and $t$-GARCH(1,1) model. Results are presented in Tables 1 and 2.

• The prior of the degrees-of-freedom parameter $\nu$ is $N(10, 5^2)$ truncated at 3, and the prior of $\omega$ is $U(0, 1)$.

<table>
<thead>
<tr>
<th>Table 1: Results from the semiparametric GARCH(1,1) model.</th>
</tr>
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<tbody>
<tr>
<td>Parameters</td>
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<tr>
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<tr>
<td>$\tau$</td>
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<td>log marginal likelihood</td>
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<table>
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<th>Table 2: Results from the $t$-GARCH(1,1) model.</th>
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<tr>
<td>$\omega$</td>
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<tr>
<td>$\alpha$</td>
</tr>
<tr>
<td>$\beta$</td>
</tr>
<tr>
<td>$\nu$</td>
</tr>
<tr>
<td>log marginal likelihood</td>
</tr>
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</table>
### Convergence performance of our sampler

- The burn-in period contains 1000 draws, and the following 10,000 draws were recorded.
- We computed the batch-mean standard deviation and simulation inefficiency factor (SIF) to monitor the convergence.
- The SIF is approximately interpreted as the number of draws needed to derive independent draws.
- For example, a SIF value of 20 means that approximately, we should retain 1 draw for every 20 draws to obtain independent draws in this sampling procedure.
- All simulated chains under the mixture error density have achieved very reasonable convergence.
- The marginal likelihood derived under the mixture error density is obviously larger than that derived under the $t$ errors.

### Bayes factor for model comparison

- Bayes factor is a ratio of the marginal likelihoods derived under a model of interest and its competing model.
- Let $\theta$ denote the parameter vector under model $A$. The marginal likelihood under model $A$ is (Chib, 1995)
  \[
  m_A(y) = \frac{\ell_A(y|\theta)p_A(\theta)}{\pi_A(\theta|y)}.
  \]
  $\ell_A(y|\theta)$ and $p_A(\theta)$ are likelihood and prior under model $A$.
- The Bayes factor of model $A$ against model $B$ is
  \[
  BF = \frac{m_A(y)}{m_B(y)}.
  \]
- $3 < BF \leq 20$: $A$ is favored against $B$ with positive evidence.
- $20 < BF \leq 150$: $A$ is favored against $B$ with strong evidence.
- $BF > 150$: $A$ is favored against $B$ with very strong evidence.
Figure 1: The estimated densities and CDFs of the one-step out-of-sample return: (1) Conditional density of $y_{n+1}$; and (2) conditional CDF of $y_{n+1}$.

- The VaRs under the semiparametric and $t$ GARCH models are $2.0324$ and $1.6643$ for a $100$ investment on S&P 500.
- Therefore, in comparison to the semiparametric GARCH model, the $t$-GARCH tends to underestimate VaR.
Motivation for localised bandwidths

- When the true error density has sufficient long tails, the leave-one-out kernel density estimator with its bandwidth selected under the Kullback-Leibler criterion, is likely to overestimate the tails density.

- One may argue that this phenomenon is likely to be caused by the use of a global bandwidth. A remedy to this problem in that situation is to use variable bandwidths or localized bandwidths.

- Small bandwidths should be assigned to the observations in the high-density region and larger bandwidths should be assigned to those in the low-density region.

Localised bandwidths

- We assume the underlying true error density is unimodal. Large absolute errors should be assigned relatively large bandwidths, while small absolute errors should be assigned relatively small bandwidths.

- We propose the following error density estimator:

\[ f_a(\varepsilon_t; \tau, \tau_\varepsilon) = \frac{1}{n-1} \sum_{i=1 \atop i \neq t}^{n} \frac{1}{\tau n^{-1/5} (1 + \tau_\varepsilon |\varepsilon_i|)} \phi \left( \frac{\varepsilon_t - \varepsilon_i}{\tau n^{-1/5} (1 + \tau_\varepsilon |\varepsilon_i|)} \right), \]

where \( \tau n^{-1/5} (1 + \tau_\varepsilon |\varepsilon_i|) \) is the bandwidth assigned to \( \varepsilon_i \), and the vector of parameters is now \( \theta_a = (\sigma_0^2, \alpha, \beta, \tau, \tau_\varepsilon)' \).
Bayesian estimate

- The prior of $\tau_\varepsilon$ is the uniform density on (0, 1).
- The parameter estimates are $\alpha = 0.093154$, $\beta = 0.893324$, $\tau = 0.763784$, $\tau_\varepsilon = 0.635660$, and $\sigma_0^2 = 0.427865$.
- The sampler has converged very well.
- The log marginal likelihood under localised bandwidths (global bandwidth) is -1835.67 (-1839.72).
- The Bayes factor of the use of localised bandwidths against the use of global bandwidth is $\exp(4.05)$, and the former is favored against the latter with strong evidence.
- The use of localised bandwidths has increased the competitiveness of the semiparametric GARCH model.

Density forecast of the one-step out-of-sample return

Figure 1: The estimated densities of the one-step out-of-sample return through localised bandwidths: (1) S&P 500 return; and (2) FTSE return.
### Application to other index returns

#### Table 3(1): Results from semiparametric GARCH (global bandwidth)

<table>
<thead>
<tr>
<th></th>
<th>Nasdaq</th>
<th>NYSE</th>
<th>DJIA</th>
<th>FTSE</th>
<th>DAX</th>
<th>AORD</th>
<th>Nikkei</th>
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<tbody>
<tr>
<td>$\sigma_0^2$</td>
<td>0.737396</td>
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<td>$\alpha$</td>
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<td>0.086032</td>
<td>0.094623</td>
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<td>$\beta$</td>
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<tr>
<td>$\tau$</td>
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<td>1.360150</td>
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<td>2.2087</td>
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#### Table 3(2): Results from the t-GARCH(1,1) model.

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<tbody>
<tr>
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<td>1.9207</td>
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<td>1.9037</td>
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### Application to other index returns

#### Table 4: Results from semiparametric GARCH (localised bandwidth).

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<tr>
<td>$\sigma_0^2$</td>
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<td>0.7610</td>
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<td>(6.20)</td>
<td>(3.81)</td>
<td>(6.44)</td>
<td>(4.92)</td>
<td>(7.40)</td>
<td>(9.15)</td>
<td>(8.06)</td>
<td>(8.28)</td>
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<tr>
<td>$\alpha$</td>
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<td>0.0958</td>
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<td>0.1085</td>
<td>0.1047</td>
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<tr>
<td>(14.60)</td>
<td>(14.63)</td>
<td>(13.95)</td>
<td>(10.61)</td>
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<td>(15.11)</td>
<td>(13.72)</td>
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<td>(15.47)</td>
<td>(17.07)</td>
<td>(16.13)</td>
<td>(13.43)</td>
<td>(8.80)</td>
<td>(23.14)</td>
<td>(17.35)</td>
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<tr>
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<td>(12.19)</td>
<td>(13.15)</td>
<td>(13.71)</td>
<td>(12.77)</td>
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<td>(27.36)</td>
<td>(23.98)</td>
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<tr>
<td>$\tau_\epsilon$</td>
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<td>(28.08)</td>
<td>(14.89)</td>
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<td>(23.53)</td>
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<tr>
<td>VaR</td>
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<td>1.9687</td>
<td>2.1207</td>
<td>1.9227</td>
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#### Table 5: A summary of marginal likelihoods.

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<th>S&amp;P 500</th>
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<th>NYSE</th>
<th>DJIA</th>
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<tr>
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<td>-1748.03</td>
<td>-1880.29</td>
<td>-1955.95</td>
<td>-1791.04</td>
<td>-2013.62</td>
</tr>
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</table>
Empirical findings

- The semiparametric GARCH with localised bandwidths is favored against the $t$-GARCH for S&P 500, Nasdaq, NYSE, DJIA, and Nikkei 225 indices. The $t$-GARCH is favored against the former for FTSE.

- The use of localised bandwidths increases the competitiveness against its competitor, the $t$-GARCH model. This is evidenced by an increased marginal likelihood for each index.

- The use of localized bandwidths slightly reduces the VaR compared to the use of a global bandwidth, but the relative change is between 0.77% to 3.98%.

- The $t$-GARCH model underestimates VaR in comparison to the semiparametric GARCH model.

Conclusion

- We approximate unknown error density by a location-mixture density of $n$ normal densities for GARCH models.

- We derived the likelihood and posterior for all parameters, and Bayesian sampling is conducted for estimation.

- The mixture error density is used to forecast the density of the one-day out-of-sample return, which is used for estimating VaR.

- The use of localised bandwidths increases the competitiveness the semiparametric GARCH against the $t$-GARCH.

- The semiparametric GARCH is favored against the $t$-GARCH for five out of eight indices.

- The $t$-GARCH underestimates VaR compared to the semiparametric GARCH.